

A. Mass Wasting

Mass Wasting

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Introduction

Mass wasting is a natural process that occurs to some extent in most forested basins in the Pacific Northwest. Certain forest management activities can accelerate mass wasting processes. Because the various slope processes generate widely variable amounts of sediment under different sets of conditions, analysts and specialists must identify specific trigger mechanisms and distinguish among the types and rates of processes active in a basin to accurately evaluate the mass wasting hazard potential. Evaluation of forest management activities in the context of terrain characteristics provides the best guidance in developing appropriate management prescriptions for reducing mass wasting.

Four types of mass wasting commonly occur on forested slopes: shallow-rapid landslides, debris torrents, large-persistent deep-seated failures, and small-sporadic deep-seated failures. Shallow-rapid landslides (also known as, debris slides, debris avalanches, or planar failures) commonly occur on steep slopes where soil overlies a more cohesive material (for example, bedrock or glacial till). Soil thickness is typically small compared to slope length or the length of the landslide. Debris in the slide moves quickly downslope and commonly breaks apart to form a debris avalanche. Shallow-rapid landslides typically occur in convergent areas where topography concentrates subsurface drainage (Sidle and others, 1985), and may deliver sediment to streams and damage roads. Susceptibility of an area to shallow-rapid failures is affected by steepness of slope, saturation of soil, and loss of root strength. Forest management activities can increase the occurrence of shallow-rapid landslides by altering these conditions; however, only a small portion (typically a few percent or less) of the landscape actually fails following timber harvest (Ice, 1985).

A debris torrent contains 70-80% solids as a highly mobile slurry of soil, rock, vegetation and water that can travel kilometers from its point of initiation, typically in steep ($>5^\circ$), confined mountain channels. Debris torrents form when landslide material liquefies concurrently with, or immediately after the initial failure. As the debris torrent moves through first- and second-order channels, the volume of material may be increased by several orders of magnitude over initial slide volume, enabling debris torrents to become more destructive the further they travel. Debris torrent initiation is generally confined to steep, colluvium-filled first- and second-order channels; debris torrents can, however, deposit large volumes of unsorted sediment and organic debris in streams of any order, typically at tributary junctions. (Benda 1990) or on alluvial debris fans. Hence, debris torrents can contribute sediment locally at the site of deposition and also downstream, increasing fine sediments in spawning gravels, causing secondary erosion of valley walls, and

damaging structures and fish habitat at considerable distances from their points of initiation (Eisbacher and Clague 1984).

Landslides and debris torrents that are deposited in narrow valley floors can create temporary dams that quickly impound water, creating small lakes. Failure of these dams can lead to extreme floods, referred to as landslide dam-break floods that can be up to two orders of magnitude greater in peak discharge than normal runoff floods. Such floods have caused extensive downstream erosion and sedimentation along entire stream segments throughout the mountainous regions of the state. Dam-break floods may also be triggered by the build-up and failure of logging slash in steep, first- and second-order streams (Type 5 and 4 waters) in managed forests. Similar to debris torrents, dam-break floods may cause erosion of valley walls (landsliding), damage to structures, and/or destroy or affect fish habitat considerable distance from their point of initiation.

Deep-seated landsliding occurs in response to strong seismic shaking, geologic weakness, or channel incision. Climatic changes, ranging from major (such as glacial-interglacial transitions), to intermediate (runs of several wet years), to short-term (extreme storm precipitation) can also trigger or accelerate deep-seated failures. The failure plane is below the colluvial layer and commonly cuts through two or more strata. These slides may persist in the landscape for a few years or centuries; in any case, debris is typically supplied from the margins of the features to a channel. The stream itself can be the cause of chronic movement, if it periodically excavates the toe of a large slide mass.

Small-sporadic deep-seated landslides are slumps that can be triggered at irregular time intervals (by storms or earth movement), and can decay to the point where they are indiscernible in the landscape. Because movement of deep-seated failures is hydrologically controlled (at least in part), land use can influence movement in certain situations.

The time scale (relative or absolute) of mass wasting in a basin is important to an understanding of the sediment mass balance of a watershed. Mass wasting events may occur on a return interval of one or two years, decades, centuries, or even millennia. While the smaller, more frequent events may cause the fresh scars seen on the landscape, the larger, infrequent events are probably the real shapers of the landscape. Both types of landslides are influential in their impact on physical resources. In a natural, unmanaged forested basin, the dynamic replenishment of material to the channels by mass wasting is essential to the diversity and health of the ecosystem.

Not all landslides deposit sediment directly in streams; sediments may be deposited on flood plains, glacial or alluvial terraces, or foot slopes, without reaching a stream. However, as basin area increases, the cumulative probability of either one small landslide entering a stream or one small

failure triggering a debris torrent with catastrophic impact on habitat conditions increases.

In this module, analysts develop information (maps and text) leading to ratings of the potential for delivery of debris and sediment to streams by mass wasting for geographic zones of the basin. These ratings are applied to the "likelihood of adverse change and deliverability" axis of the cumulative effects rule matrix. Mass wasting processes occur naturally. We attempt to isolate human activities (specifically forest practices) that contribute to "non-natural" mass wasting events and processes. Altering these activities can prevent such occurrences.

Critical Questions

The purpose of the mass wasting module is to guide development of information necessary to address several questions critical to understanding the mass wasting processes in a watershed:

What are the potential sediment sources in the basin?

Is there evidence of, or potential for mass wasting in the watershed?

What mass wasting processes are active?

How are mass wasting features distributed throughout the landscape?

What physical characteristics are associated with these features?

Do landslides deliver sediment to stream channels or other waters?

Do forest management activities create or contribute to instability?

What areas of the landscape are susceptible to slope instability?

What is the relative contribution of sediment from mass wasting compared with other sources?

Assumptions

A number of fundamental assumptions underlie the approach developed here. The most fundamental requirement is that the analysis is based on the best available scientific information and techniques. Thus, the module analysis methods themselves are designed to change as newer methods are developed. The underlying assumptions and analysis framework, on the other hand, are not. Rather, these assumptions dictate a rigorous, yet flexible, framework for analysis. Our primary assumptions include:

- Aerial photographs can be used to interpret and document the history of land use and mass movement in a basin. Although some features are obscured by vegetation, most landslides of significant size can be identified on aerial photos, as can the tracks of debris torrents and dam-break floods.
- Identification of existing mass-movement features can be used to predict the likelihood of future instability. Areas prone to these processes can be mapped based on physical characteristics, as interpreted from aerial photographs, topographic maps, and geologic and soils maps.
- Although most landslides are at least partly caused by natural processes or events, in most cases, the initiation or acceleration of mass movement can be attributed either to natural conditions or to forest practices. Mass-movement features associated in time and space with logging or roading activities are assumed in Level 1 to be caused by forest practices.
- It is feasible to extrapolate from one sub-basin to another having similar characteristics, based on information obtained from maps and aerial photos.

Overview of Approach

Mass wasting is one of several sediment sources in a watershed. In order to understand the relative importance and contribution of sediment from mass wasting, a sediment budget approach is suggested.

A sediment budget is defined as a quantitative description of sediment production rates, transport, storage, and output by the different processes in a drainage system (Dietrich and Dunne, 1978). (See Swanson and others (1982) for a description of the sediment budget approach.) This discussion focuses on the supply aspect of a sediment budget since routing of delivered sediment is addressed in the channel module. For Washington state

watershed analysis, quantification and analysis is concentrated on sediment production and delivery from mass wasting, road erosion, sheetwash and gully erosion from hillslopes, and surface erosion from landslide scars. Other processes include stream bank erosion, dry ravel, tree throw, and animal burrowing in addition to non-forest management sources such as cattle or agricultural and urban development. Although these processes are not specifically named in watershed analysis, if they are determined to be a significant source of erosion, they should be addressed.

Prior to data collection, team members need to identify and discuss the major sediment sources in the watershed administrative unit (WAU). Sediment sources can be identified with the use of aerial photographs and field reconnaissance, and by communication with land managers who are familiar with the WAU. Based on discussions, team members must decide who will assess the processes associated with sediment sources. For example, mass wasting is generally not a major process in east-side forests, while surface erosion from roads, hillslopes, or agricultural practices is more common. In this case, team members may focus on surface erosion processes by dividing the tasks among available qualified team members. The result is a more thorough quantification of sediment inputs from each source. Simply stated, the team must decide how best to use available analysts and time. Another example may be in surface erosion of landslide scars until ground cover is established. In west-side forests, mass wasting is commonly a dominant process, but after the initial mass wasting event, landslide scars may continue to produce sediment through surface erosion. Depending on the work load, analysis of the sediment source may be included in the mass wasting module or the surface erosion module. Once the dominant sediment sources have been identified and division of labor has been determined, the methodology for assessing mass wasting is conducted. When comparing the relative sources of sediment in a basin, attention should be given to the time scale at which various processes are contributing and to compare sources or rates in the same units.

The mass wasting assessment is conducted using aerial photographs, maps and field observations. Based on this information, the analyst interprets mass wasting processes relative to the critical questions. Watershed analysis requires the mass wasting analyst to develop information to address each critical question. The method developed in this manual describes the standard mass wasting assessment.

A series of exercises designed to either confidently answer the key questions, or to identify more detailed information necessary to do so, is developed in the module (Figure A-1). The objective of these exercises is to generate information sufficient to establish:

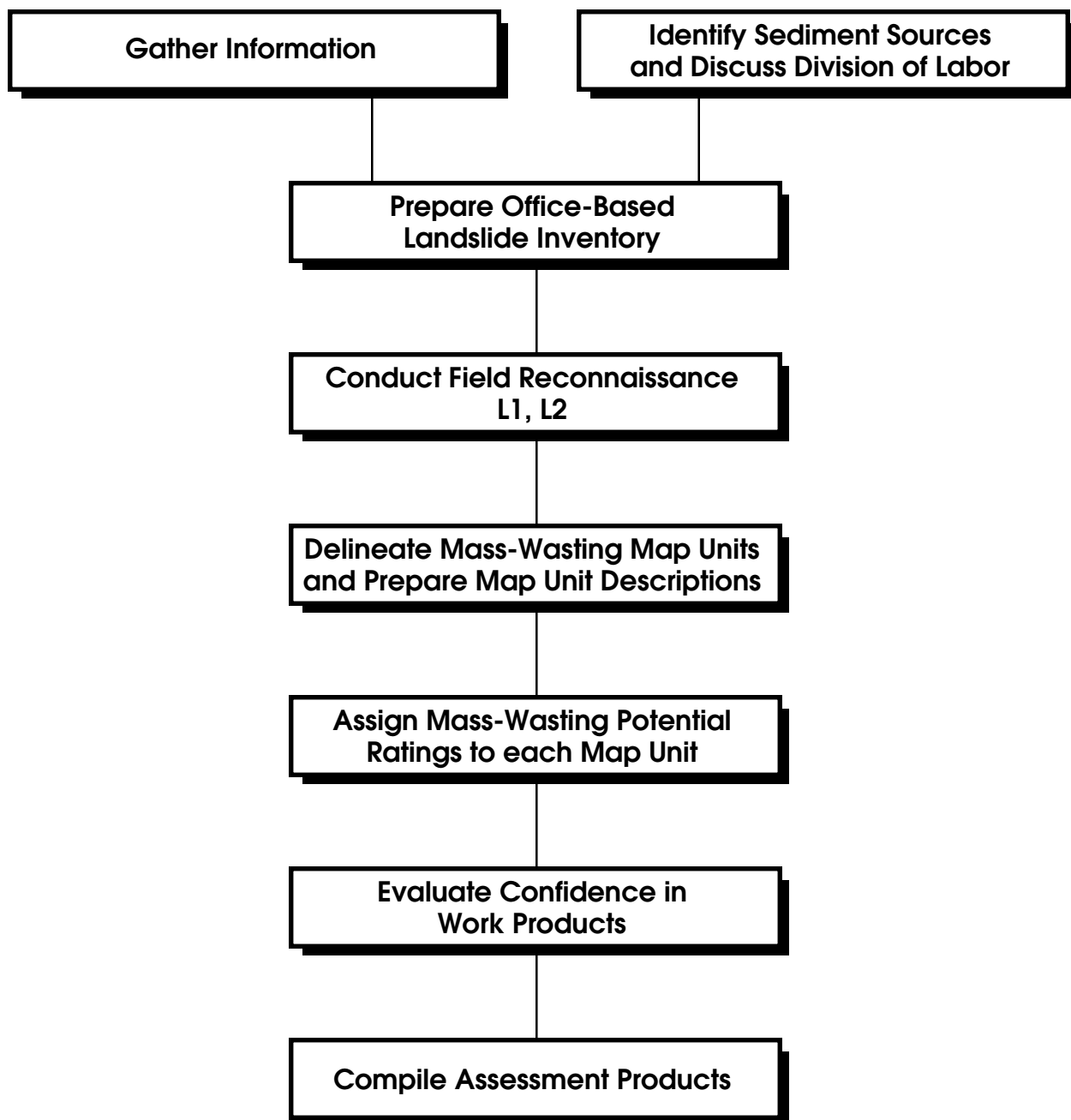
1. The mass wasting features and processes (shallow-rapid landslides, debris torrents, and deep-seated failures) active in the basin.
2. Portions of the landscape having similar inherent physical characteristics relative to mass-movement behavior.
3. The relative potential for mass wasting impacts associated with the landscape units.

The analyst first conducts an inventory of landslides in the watershed. The assumption underlying this approach is that many of the activities potentially triggering mass wasting have been conducted in the past in some or all of the areas sharing similar erosive characteristics. These prior “experiments” can be used to infer future erosion response.

An interpretation of the mass wasting potential is made by associating the occurrence of landslides with terrain or geologic features. These associations form the basis for the mapping of mass wasting map units in the watershed. Mass wasting map units are drawn for each area with similar mass wasting characteristics and triggering mechanisms. These mechanisms are the specific geomorphic processes that appear to contribute to mass wasting (i.e., increased groundwater and pore pressure, over-steepened or over-loaded slopes, excess water drainage, etc.). Unique units are described if the mass wasting processes are similar (i.e., shallow debris flow), but the triggering mechanisms are different (i.e., roads versus loss of root strength on hillslopes).

The mass wasting potential for the units are qualitatively rated guided by criteria based on the watershed information according to likelihood of occurrence. These ratings determine the level of “potential hazard” for use in the rule call at later stages of the assessment.

Figure A-1: Mass Wasting Module Flow Chart



Qualifications

Analysts conducting the Level 1 mass wasting assessment should possess a knowledge of hillslope processes (including erosion, transport, and deposition) and their relationship to forest management activities. Skill in aerial photo interpretation, landform analysis, and recognition of mass-movement features (including shallow-rapid landslides, debris torrents, and deep-seated failures) in a variety of geomorphic settings is necessary.

The education associated with these qualifications includes a college degree (preferably post-graduate) in geology or geomorphology; or in a related field, such as geotechnical engineering, soil science, geophysics, or forest engineering, with a significant amount of course work or other training in geomorphology and/or mass-movement processes.

In addition to the qualifications for Level 1, Level 2 specialists should be familiar with the methods of sediment budgeting, routing of mobile mass-movements, and slope stability modeling.

Table A-1. Mass Wasting Assessment Checklist

Below is the mass wasting assessment checklist, which helps guide the mass wasting team leader through the watershed analysis.

Task	Scheduled	Completed	Reviewed
Assemble startup materials:			
• official WAU base map			
• aerial photographs			
• orthophotos			
• geology maps			
• soils maps			
• topographic maps			
Team coordination meeting - discuss sediment sources and division of labor; schedule approx. field days with other module participants.			
Landslide Inventory:			
• aerial photo inventory			
• complete Form A-1			
• record on to Map A-1			
Formulate tentative mass wasting map units			
Field reconnaissance			
MWMU designation:			
• MWMU descriptions (Form A-2)			
• Mass Wasting Summary Table (Form A-3)			
• Delineate MWMU polygons on Map A-2			
Summary report			

Background Information

Maps

Official WAU base map

Topographic maps of the assessment area

U.S. Geological Survey 7.5-minute series (or largest scale available). See USGS index to topographic map coverage for Washington (USGS, 1992). Maps are available from commercial dealers, DNR Photo & Map Sales (Olympia (360) 902-1234), and USGS Western Mapping Center (Denver).

Geologic maps

- a. USGS or DNR Division of Geology & Earth Resources (DGER) maps at 1:100,000 (or larger) scale. See DGER indices to geologic mapping (Manson 1984, 1994, 1995 or county bibliographies); or contact

DNR - Division of Geology and Earth Resources

Olympia: (360) 902-1450

Spokane: (509) 533-2484

USGS - Earth Science Information Center

Spokane: (509) 353-2524

- b. For areas administered by the U.S. Forest Service, maps of geologic resources and conditions (GRC) might be available; contact the appropriate forest supervisor's office, zone engineering office, or district ranger station.

Soil maps

There are a variety of sources for soil maps:

- a. State soil survey (for nonfederal forest lands) - maps available from DNR Photo & Map Sales (Olympia), or in township plots from GIS data; DNR Information Technology Division (360) 902-1515; text volumes available for purchase or examination at DGER.
- b. Soil surveys published by the U.S. Natural Resources Conservation Service (formerly Soil Conservation Service) (particularly after about 1980) typically utilize the same map units as the state survey, and contain additional information; contact local NRCS office.

- c. For national forests, soil resource inventory (SRI) maps and information might be available; contact local USFS office.

Other maps that may be helpful if available:

- a. Landslide maps have been published covering some parts of the state. Consult the WDGER indices for availability. For national forests, consult the GRC maps.
- b. Mass-wasting hazard maps have been produced for a few regions, mostly in urban areas. Consult the DGER indices.
- c. GIS models of slope form and stability, based on digital elevation data, are becoming available. The DNR slope-morphology model, based on slope gradient and shape (convergent-straight-divergent), can be reproduced using the information in Shaw and Johnson, (1995); the GIS-AML (ARC Macro Language) program is available from DNR Information Technology Division - Linda Tamayo, Computer Information Consultant (360) 902-1547). The model addresses debris avalanches (e.g. shallow-rapid landslides) only. Other similar models are also being developed (Montgomery and Dietrich, 1994; Wu and others, 1993).
- d. The DNR GIS also contains digital data on precipitation zones, forest roads and canopy/core density of vegetation from Landsat. Contact DNR Information Technology Division for availability. (Analysis teams working through the DNR basin priority list will have preference in getting DNR GIS products and assistance.)
- e. Maps of land use, vegetation cover, etc., might be available from the USGS, local planning agencies and/or landowners. Check with hydrology module analysts who also use precipitation and vegetation information.

Photographs

The mass wasting assessment is built around the examination of aerial photographs. Although it is preferable to examine a complete series of air photos spanning decades, time constraints in Level 1 may necessitate using a more limited number of photo sets. Analysts should examine as many photographs as necessary to obtain an adequate basic understanding of the mass wasting behavior of the basin.

- a. Indices of most aerial photo flights over Washington can be obtained at DNR Photo & Map Sales. Prints of photos available through DNR can be ordered there; prints for some areas and times must be obtained from the

USFS, USGS, Agricultural Stabilization and Conservation Service (USDA), the National Archives, commercial firms, or other sources.

Photographs at about 1:12,000 to 1:16,000 scale are best for detection of small features; scales of 1:24,000, 1:40,000, and 1:62,500 cover more area with fewer photographs, and are better for terrain evaluation, but provide reduced resolution. Color photographs are preferred, because they allow detection of subtle differences in tone of soil, vegetation, etc.; however, they are more expensive and produced less often.

- b. Orthographic aerial photographs (orthophotos) of townships and quarter-townships are available for most of Washington; contact DNR Photo & Map Sales.

Equipment

- A mirror stereoscope is necessary for efficient mapping from aerial photographs.
- Mylar (or other material) overlay sheets for individual photos (9" x 9") are useful for initial mapping.
- Two mylar sheets, for base map overlays, are required.

Other information

- Environmental and land use history: Information on the incidence of forest fires, recent major storms, and human activities may be helpful in interpreting apparent mass-movement features (particularly in Level 2 analysis). Such information can be obtained from geologic and geomorphic studies (see DGER bibliographies listed in Manson, 1984, 1994, 1995); vegetation studies (e.g., the USFS guides to plant associations for the national forests); and compilations of climatic data (from the National Weather Service) and streamflow data (USGS), both available in paper and CD-ROM formats. Local landowners, residents, technical personnel, etc., may also provide some information.

Analysis Procedure

Standard Methods

The following procedures constitute the standard methodology. Level 1 analysts may rely solely on the methods provided here. Additional methods for resolving uncertainties are provided.

The purpose of the landslide inventory is to collect information that will aid in understanding the distribution, timing, and relative size of mass wasting processes in the basin, and thus be useful in creating mass wasting map units. The primary intent of this module is to evaluate and map the potential for delivery of mass wasting hazards, for use in the synthesis and prescriptions modules; therefore, do not spend an inordinate amount of time on the inventory.

More time is allowed in Level 2 and the methods are more flexible, so that detailed analysis can address the specific problems identified in a WAU. In particular, the relationships between land use activities and landslide processes are to be identified more accurately and precisely and with greater spatial resolution. The result is a higher level of certainty in the information and mass wasting potential hazard ratings.

If the analysis is beginning at Level 2, the maps, tables, and summaries normally prepared in Level 1 must be produced. If a Level 1 analysis has already been conducted, the Level 2 assessment builds upon the information already gathered, especially the mass wasting mapping. Then, Level 2 is intended to answer the important questions that were not resolved by the Level 1 investigation, and to further isolate and identify mass wasting problem areas and trigger mechanisms.

1. Landslide Inventory

- a. Identify the parts of the watershed in which landslides are most likely, based on slope gradient, unstable soils, and storm-water input. Focus attention on sub-areas having mass wasting problems in forest lands.
- b. Select appropriate set(s) of aerial photographs:
 - The most recent set (small- to medium-scale) available;
 - Sets that depict pre-logging conditions (if possible);

- Sets taken at time intervals (8 to 12 years) that allow appraisal of changes in slope instability (photos taken a few years after major logging operations or big storms are helpful).
- c. Examine the aerial photographs in stereo (begin with earliest years to most recent) to identify landslides, debris torrents, and other erosion features; map the mass wasting features. Initial mapping may be on photo-overlay (9" x 9") sheets, or directly onto a topographic base map. Transfer the features onto a mylar overlay (*Map A-1: Landslide Inventory*) placed on the WAU base map.
- d. Assign an identification number to each feature. The identification system must provide a distinctive geographic identifier to each landslide in the inventory, so that readers can correlate features between maps, inventory lists, and text. The system explained below is strongly recommended, but other identification schemes that provide equal or better utility are allowed. UTM and latitude/longitude coordinates have particular usefulness to GPS and GIS applications for data management and display.

- Landslide Identification Number Example: 13/05E-26L278(_____) See explanation below:

- Township: (e.g., from example, **13**/)
- Range (E or W of Willamette meridian): (e.g., from example, **05E**)
- Section: (e.g., from example, **-26**)
- A letter representing the initiation location of the feature by each 1/16 (40 acres) section (see diagram; e.g., D, G, R, ...): e.g., from example, **L**

D	C	B	A
E	F	G	H
M	L	K	J
N	P	Q	R

- Number of the feature (within the 1/16 section) (in consecutive numbers; e.g., from example, **L2**).
- Year of the photograph on which the feature first appears: from example, **78** or;
- (Optional) Actual date of the slide if known (e.g., year/month, 82/02).
- e. Complete the mass wasting assessment data form (Form A-1: Mass wasting Inventory Data), found at the end of this appendix. On the form,

arrange the observations by smaller sub-basins, beginning at the upstream end of the watershed. Organization of the inventory in this manner, combined with recording the appearance and size of features by photo dates (see below), allows the analyst to appreciate the cumulative distribution and timing of mass wasting downstream through the basin.

For each feature, fill in as much of the following information as possible. Less important items, or those with a level of detail not practical for a Level 1 assessment, are marked “optional.”

- Sub-basin
- Landslide Identification Number
- Mass Wasting Map Unit - To be filled in after delineation of map units.
- Landslide Processes and Certainty of Identification - record the following information:

Process:

SR Shallow-rapid landslides
DT Debris torrent
LPD Large-persistent deep-seated failure
SSD Small-sporadic deep-seated failure

Other descriptor(s), as appropriate

Certainty of identification (optional) - Based on the number and expression of slide-related features, these designations can be modified following field reconnaissance:

d definite
p probable
q questionable

For example, a debris slide that is clearly recognized would be identified as SR/d; a questionable, large slump-earthflow might be LPD/q. (See Wieczorek, 1984).

- Year of initiation and size of failure - Note the date (or flight number) of the aerial photograph set in the column heading on Form A-1; arrange the flights from oldest (left column) to most recent (right), preserving the last column for features initiated after the latest photos (i.e., identified in the field).

- Record the approximate area of the slide in the column corresponding to the photo set being examined. For landslides, find the size by measuring directly off the photograph, or use the categories below. A template of size categories, calibrated to the average photo scale, will be useful in basins with many landslides.

<500 yd ²	=	small
500-2000 yd ²	=	medium
2000-5000 yd ²	=	large
>5000 yd ²	=	very large

- For debris torrents, indicate the type and length of stream affected. If multiple photo sets are examined, note changes between photograph dates.
- Note the area of any obvious enlargement of features in the appropriate columns.
- For older features not active during the photo-documented history, note approximate age and probability of future movement in the first column, using the following codes:
 - a** ancient, $\odot 10^2$ to $\odot 10^6$ years old
 - d** dormant, suggests it has been or might be rejuvenated
- Sediment delivery to streams or other waters - note if sediment is delivered to a stream, and the type of receiving water(s):
 - N** no sediment delivered
 - Y** sediment delivered - add water-type number of nearest receiving water
 - I** indeterminate
- Surface erosion of scar - estimate of percent of landslide scar unvegetated and presumed to contribute fines to stream system.

- Land use activity associated with the feature - Record information on associated activities:

Harvest activities:

CC Clear-Cut

PC Partial Cut (crown opening reduced by 50% or less)

Approximate stand age at time of failure:

0-20 years = younger than age of root-strength recovery

20-50 years = younger than the age of hydrologic recovery

>50 years = hydrologic and root recovery

Yarding method: tractor, high lead, other

Forest roads: note type, stream crossing, landings, etc.

Other forest practices associated with slope failure

No associated forest land use

Wildfire: note time since most recent fire

Other (non-forest) land use(s) associated with failure

- Geomorphic characteristics of the slope around the feature - Include:
Gradient (or range)

Form (concave, convex, planar, headwall, inner gorge, flow topography, etc.)

- Soil type (*optional*) - Record the general soil type (residual, colluvial, glacial, etc.), and texture (coarse, fine, mixed)
- Bedrock (*optional*) - Record the type of rock or regolith underlying the landslide; if possible, note the formation name
- Elevation (*optional*) - Record the initiation elevation or precipitation zone of the feature; note whether the feature might be affected by conditions related to elevation or climate (rain-on-snow events, etc.)

- Comments - Note additional information as appropriate or other effects such as any effects on streams, structures, roads, utilities, populated areas, etc.

2. Field Reconnaissance

The analysts should conduct a brief inspection of the basin to evaluate whatever can't be seen on or interpreted from the maps and photographs, or to help resolve major uncertainties regarding:

- a. The physical conditions associated with landsliding, and the particular characteristics that should be used in establishing the mass wasting map units;
- b. Land use trigger mechanisms associated with slope instability (e.g., road sidecast failure, undersized culverts);
- c. Delivery of sediment to streams, public works, etc.;
- d. Extrapolation of map units to lesser-known areas.

3. Mass Wasting Map Units

In this step, the basin landscape is partitioned into map units, based on physical characteristics contributing to slope instability and the potential for landslide sediment to enter streams or affect other public resources.

- a. Inspect the landslide inventory data and map, noting the geologic and geomorphic factors associated with each mass wasting feature. What mass wasting features are present in the basin, and how are they distributed?
- b. Define the mass wasting map units (MWMUs) as areas of terrain having similar physical characteristics and mass-movement behavior. (Do not differentiate map units based on the presence or absence of management activities at this point; landscape sensitivity to management practices is evaluated in the hazard ratings.) When designating MWMUs, consider the following characteristics related to slope instability:
 - Landslide processes and densities
 - Slope gradients and landforms
 - Bedrock types and structures
 - Soil materials

- Potential for sediment entry into streams or lakes (high, remote, NO)
- Slope hydrology
- Natural vegetation types
- Climatic zones, storm-water input rates
- Other appropriate factors (hollow spatial scale, hollow density)

In addition, each MWMU should be unique with respect to at least one of the following: process, density, delivery.

The number and nature of map units designated in a WAU will depend on the geomorphic complexity of the basin. Although the analyst is free to design map units appropriate to the area being examined, some consistency in units (particularly among adjacent basins) would be useful and practical. (For guidance, see Rib and Liang (1978); Fiksdal and Brunengo, (1981); Varnes (1984); Sidle and others (1985); Howes and Kenk (1988); Chatwin and others (1991).)

- c. Outline the map units on a second overlay (Map A-2 Mass Wasting Potential). Label the MWMUs by number; for units with multiple polygons, include a polygon number for each (e.g., 3-1, 3-2, ...).
- d. Summarize information on each MWMU into a concise summary form (see Form A-2, Mass Wasting Map Unit Description Form). Write a brief description of the physical characteristics, mass-movement history and behavior, sediment-delivery characteristics, and associations with forest practices, for each map unit. Descriptions should be as quantitative as possible. Refer to the example on Figure A-2.

Distributions and types of existing landslides are important in designating the MWMUs. If many slides were located adjacent to the main stream channel in an inner gorge, the gorge could be identified as a separate map unit. In many places, shallow landslides are associated with the toes or headscarps of large slump-earthflows; thus, deep-seated slides (or specific parts of them) could be defined as map units. Note whether mass wasting features are persistent sources of coarse or fine sediment, either from continued enlargement, active earthflow, or surface erosion of landslide scars.

- e. Tabulate, for each MWMU, the number of features (by type) associated with various land use activities (on Form A-3 Mass Wasting Summary Table) (Figure A-3).

Figure A-2: Example of MWMU Description Form

Form A-2 Mass Wasting Map Unit Description Form

MWMU Number:	1
Description:	Steep (>65%) relatively straight slopes adjacent to stream channels
Materials:	Shallow permeable soils, containing both colluvium and glacial sediments, mantling competent, but fractured, andesitic bedrock
Landform:	Inner gorge: a narrow inset V-shaped valley characterized by steepening of slope gradient above stream channels, with a more-or-less distinct break in gradient between the relatively planar inner-gorge slope and the lower gradient hillslope above. Relief of the inner gorges (measured from the slope break) varies between about 30 to 150 feet (10 to 30 meters). The inner gorge slope typically runs directly to the active stream channel (that portion inundated during high flows) with little or no intervening low-gradient flood plain or terrace.
Slope:	> 65% (33%) measured on site
Elevation:	1,600 ft. - 3,800 ft. (490 to 1160 meters)
Total Area:	269 ac. (optional) (109 hectares); 0.5% of the total WAU area
MW Processes:	<p><i>10 road-related shallow rapid landslides</i></p> <ul style="list-style-type: none"> • 5 side-cast failures • 3 fill failures, all at stream crossings, 2 of which developed into debris torrents • 2 down-slope shallow rapid landslides associated with concentrated surface-water discharge from roads <p><i>6 non-road related shallow rapid landslides</i></p> <ul style="list-style-type: none"> • 5 in clearcut harvest units (each of which was less than 20 years old) • 1 in mature forest with no previous forest practices
Non Road-related	
Landslide Density:	(optional) 1 landslide per 269 acres observed over the 30-year record (0.08 landslides per square mile per year)
Forest Practices	
Sensitivity:	<ul style="list-style-type: none"> • High sensitivity to roading • High to moderate sensitivity to clearcut harvesting (sensitivity to other harvest techniques unknown)
Mass Wasting	
Potential:	High; there is both a potential for landsliding under unmanaged conditions and a high sensitivity to forest practices
Delivery Potential:	High

Figure A-2: Example of MWMU Description Form (Continued)**Delivery Criteria**

Used: Steep slopes adjacent to stream channels (no intervening low-gradient area for deposition); historical delivery observed

Hazard-Potential

Rating: High

Trigger

Mechanism(s): *Roads:*

- Failure of sidecast material placed on slopes of gradient > 65%
- Fill failures at stream crossings. Road washouts at stream crossings may result from plugged culverts. Culverts may become blocked by woody debris and bedload transported down the steep inner-gorge channels during storms.
- Discharge of surface water on to steep slopes. Two shallow rapid landslides occurred below ditch-relief culverts draining on to steep slopes.

Harvest:

- Increased landslide rates are associated with clearcut harvests within inner gorges. This increase is probably the result of reduced soil strength caused by loss of root mass.

Confidence:

- High confidence that the potential hazard rating for this MWMU is high: landslides occur naturally in unmanaged areas within this MWMU and there is an increase in landslide activity in those areas affected by past forest practices.
- Low confidence, however, that the entire area mapped as MWMU 1 is unstable. Inner gorges are often very narrow and may be obscured on aerial photos by full forest canopy. For that reason, many inner gorges cannot be confidently delineated from contour lines on a topographic map. For most cases, identification of inner gorges relied on interpretation of aerial photographs and field identification. MWMU 1 polygons are mapped conservatively in an effort to include all inner-gorge slopes; for that reason some stable areas are undoubtedly included within the MWMU area. Likewise, it is likely that some inner gorges were missed. The final determination as to whether or not any particular slope falls within MWMU 1 depends upon actual field conditions and should be based upon the description given above.

Comments:

Timber harvest may also affect slope hydrology in a manner that could increase the potential for mass wasting. For example, snow accumulations (and water equivalent) in clear-cuts are commonly deeper than under forest canopy. Melting of the snowpack can result in greater inputs of moisture to the soil within a clearcut than within a mature forest (e.g., during a rain-on-snow event). Larger moisture inputs result in more extensive saturation of the soil and greater likelihood of shallow-rapid landsliding. The spatial distribution of this effect is difficult to predict in this area because of the extremely variable permeability of the underlying bedrock (fractured andesite).

- f. Extrapolate map units and descriptions to other areas. When appropriate, the analyst can extend the mass wasting map units to areas having no photographic record, or areas that have not been intensely affected by

ACTIVITY	MASS WASTING FEATURE				Totals
	Shallow Rapid LS	Large Persistent Deep-Seated Failures	Small Sporadic Deep-Seated Failures	Debris Torrent	
Clear Cut 0-20 years	2	0	1	1	4
Clear Cut 20-50 years	1	2	0	1	4
Partial Cut	0	1	0	0	1
Road	6	0	0	3	9
Stream Crossing	1	0	0	1	2
Landing	1	0	0	0	1
Other Forest Practices	0	0	0	0	0
Wildfire	0	0	0	0	0
Mature Forest	0	0	0	0	0
Non-Forest Land Use	2	0	0	0	2
Totals	13	3	1	6	23

Figure A-3. Example of Mass Wasting Summary Table (Form A-3)

harvesting or roading. This allows extrapolation of the predictive mass wasting potential ratings as well.

For an inference to be valid, the known area and the unmapped area must be comparable in materials, landforms, and (to the extent known) erosion

processes. Important characteristics that should be similar include all of those used to define the known MWMU (see b. above), especially:

- Slope form and gradient
- Bedrock and soil types
- Elevation, climatic zone
- Vegetation type

The greater the similarity of these characteristics between the known and unknown areas, the greater the confidence will be in the extrapolation of hazard ratings. If there are large differences between the areas, extrapolation should not be attempted, and indeterminate ratings should be assigned to the unmapped or unknown area.

4. Mass Wasting Hazard Potential Ratings

Ratings of the potential hazard of mass wasting debris or sediment to be delivered to streams and other public resources are assigned to the mass wasting map units. The ratings are determined on the basis of occurrence of landslides in the past (recognized in the landslide inventory and Form A-3), the relationships among forest practices and instability processes, and the likelihood that debris or sediment will be delivered to sensitive locations or waters (mass-wasting map unit descriptions Form A-2). Each element is part of the rating.

a. Consider the following factors, in combination, when making hazard ratings:

- What is the natural potential for mass wasting processes?
- Are the mass wasting processes associated with forest practices?
- What is the potential for sediment to be delivered to streams or other waters?

The specific criteria used to evaluate delivery potential and predict the length of landslide tracks should be explicitly stated. A method to predict debris torrent run out is in Benda and Cundy, 1990, and channel characteristics associated with landslide dam-break floods are described in Coho and Burges, 1994. A synthesis of runout path length methods for shallow-rapid landslides, debris flows, and dam-break floods is in Kennard, 1994.

Because of regional variability in mass-erosion rates across the state, and the limitations inherent to Level 1 methods, it is not possible to define specific quantitative criteria for hazard rankings. Rather, they are assigned to map units within the WAU relative to the rest of the basin (and considering adjacent basins, if that information is available). The ratings address the most likely sediment sources in the watersheds; some basins may not contain a MWMU with a high hazard rating, while others may not include any low ratings.

The objectives of Level 1 are to identify with high confidence areas with low mass wasting hazard potential, and approximately differentiate the areas with moderate, high, and indeterminate levels of hazard, the criteria are applied in the order given below:

1. *Low:* Mass-movement features are rare to nonexistent; factors contributing to slope instability are practically absent; and there is little or no sediment delivery to water from mass wasting. This rating should be applied so as to minimize the possibility of masking small high-hazard areas within larger areas with low potential ratings (false negatives).
2. *High:* Landslides are common and there has been a debris torrent, or there is significant potential for either; mass wasting is associated with forest practices; and debris and sediment are typically delivered to streams or other waters.
3. *Indeterminate:* Landslide density in the map unit is unknown; the future behavior of slopes is unpredictable; the sensitivity to forest practices is unknown or unpredictable; or the likelihood of sediment delivery is unknown.
4. *Moderate:* All other combinations of landslide density, probability, sensitivity to forest practices, and sediment deliverability are rated moderate in Level 1.

- b. Hazard-potential ratings for mass wasting are derived from both mass wasting potential and delivery potential. (See Table A-2.) Both components of the rating should be included on the MWMU description form with appropriate justification, evidence, and confidence addressed (see example Form A-2). A summary table of mass wasting and delivery potential and hazard-potential ratings (Figure A-4) is helpful, but not required.

Indicate the ratings for hazard potential assigned to the mass-wasting map units (using the shading patterns indicated) on the MWMU overlay (Map A-2) and note and justify ratings in the descriptions of the mass-wasting map units (Form A-2). Figure A-5 shows an example of a

Table A-2. Ratings for Potential Hazard of Delivery of Debris and Sediment to Streams by Mass Wasting

		Mass Wasting Potential		
		Low	Medium	High
Delivery Potential	Low	L	L	M
	Medium	L	M	H
	High	L	M	H

Figure A-4: Example of Mass Wasting and Delivery Potential Summary Table (Form A-4)**Form A-4: Summary of Mass Wasting and Delivery Potential**

MWMU	Mass Wasting Potential	Delivery Potential	Potential Hazard Rating
1	High	High	High
2a	Moderate	Moderate	Moderate
2b	Moderate	Low	Low
3	Low	Low	Low
4	High	Moderate	High
5	High	Low	Moderate
6	Low	Moderate	Low
7	Low	High	Moderate

hazard-potential map. It may be desirable to designate mass-wasting map units on the original 1:24,000 map overlay in color for use by the assessment and prescription teams; however, maps need to be reproducible in black and white, and all polygons should be clearly labeled with the unit number, optional polygon number, and hazard shading.

- c. Prepare a concise statement, to be included in the description for each mass-wasting map unit, describing the basis for the assignment of the hazard-potential rating, including the sensitivity to specific forest practices and likelihood of delivery of debris and sediment. Justify your calls with specific references pertinent to your analysis.

These ratings of potential mass wasting hazard are taken to the routing and synthesis modules, and applied to the "likelihood of adverse change and deliverability" axis of the cumulative-effects rules matrix.

- d. Write a statement on Form A-2 linking mass wasting events to trigger mechanisms. Specific details are necessary to set appropriate prescriptions (e.g., landsliding caused by road sidecast failures, debris torrent initiated by failure of fill at stream crossing).

Analysts should evaluate the potential for continued occurrence of mass wasting due to outdated or substandard forest practices (e.g., yarding across streams, orphaned roads), because they may continue to contribute to landsliding and stream sedimentation.

- e. Prepare a statement on Form A-2 on the confidence in the analysis. If this has been a Level 1 analysis, include recommendations or guidance on the appropriateness or necessity of Level 2 analysis, including the specific questions or uncertainties that should be addressed. A brief summary evaluating the certainty level of the assessment and the work products must also be included in the final mass wasting assessment report.

Consider the following factors that can influence confidence in the mass wasting assessment:

- Complexity of the basin
- Extent of field-checking and accessibility to basin
- Scale and range of aerial photograph coverage and length of record
- Quality and quantity of other information
- Additions to or deviations from standard methods
- Skill level of the analyst

Tolt Watershed
Mass Wasting Units

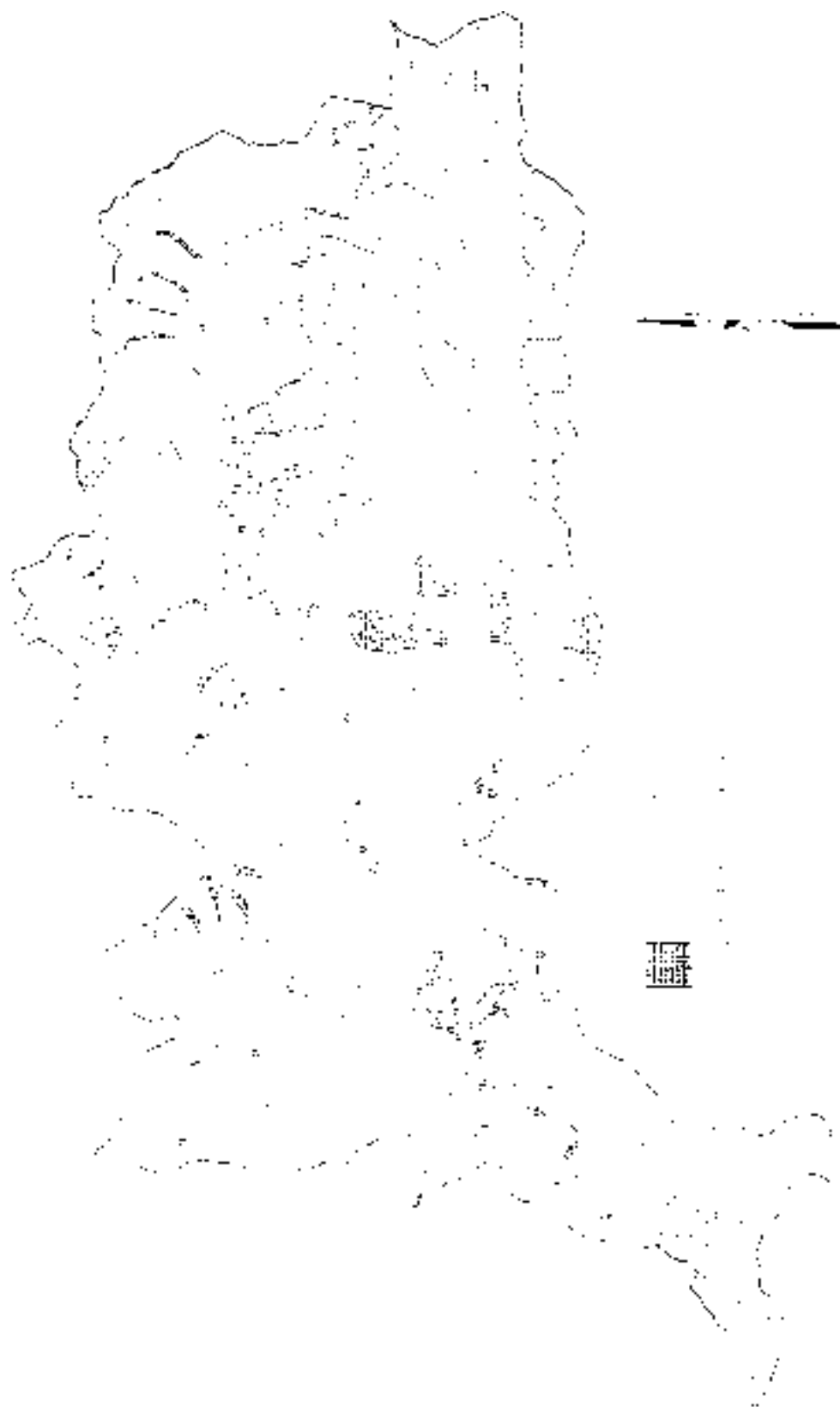


Figure A-5: Example of mass wasting hazard potential map

Suggested Methods for Use in Level 2 Assessments

There are a number of ways to improve the analysis to better address the critical questions or resolve uncertainties that Level 2 analysts could employ. Some of these are described below:

1. Expand and improve the landslide inventory mapping. In many cases, the Level 2 work will include additional aerial photo interpretation (more area, or more sets of photographs), supplemented with more extensive field verification. Increase the level of certainty in the contributing physiographic factors (geologic, climatic, etc.), trigger mechanisms, the linkages between forest practices and landsliding (these links are important in developing forest management prescriptions), delivery of sediment to streams, and the effects on stream function, habitat, and capital improvements.
2. Identify the mass wasting potential from the existing forest roads. Analyze the road network for potential to fail, for the landslide to impact identified downstream resources, and rank unstable sites relative to each other by the potential to impact resources.

A field-based method to assess and rank risks to watershed resources from forest road landslides (Kennard, 1994) is available from the Weyerhaeuser Company, Tacoma, WA.

3. Obtain a better understanding of deep-seated failures. Analyze time-series of aerial photographs, precipitation records, and other information to establish chronic or event timing, and to detect any relationships between land use and the initiation or movement of deep slumps, slides, and earthflows. Field-check those features that seem to be affecting streams, structures, etc., to determine specific causes and consequences.
4. Further differentiate debris torrents, and try to understand their behavior. Although the indicators of debris flows and dam-break (or other hyperconcentrated) floods can seem similar on aerial photos, there are differences in the ways they begin and act, the parts of the stream systems they affect, the deposits they leave, and the kinds of hazards they pose (Pierson and Costa, 1987; Costa and Schuster, 1988; Johnson, 1990; Coho and Burges, 1991). Thus, it is desirable to discriminate between them; in particular, note the relationships between initiating events and land use activities, and the run-out behavior that might threaten stream habitat, structures, or public safety.

5. Improve the quality and resolution of the map of mass wasting units. This could be done by increasing the number of factors included in the delineation of the MWMUs, or by adapting and using an existing method of landform classification (such as the system of Howes and Kenk, 1988). This will increase the precision of the material-process-landform associations for the basin, and the connections between mass-movement and land use activities.
6. Compute landslide rates (number/area/time) or material transfer rates (volume/area/time), using a sequence of historical aerial photographs supplemented by field inspection. Determine the effects of particular forest practices (or other land uses) on mass-erosion rates over time. See Howes (1987) for an example of quantitative methods of rating and extrapolation of post-logging landslide-hazards; and Sidle and others (1985), Ice (1985), and Pentec Environmental (1991) for comparisons of rates derived from other studies.
7. If other Level 2 assessment methods do not resolve the outstanding issues, the specialist team could construct a partial sediment budget for appropriate areas of the basin (Swanson and others, 1982). This might be done to:
 - a. Tie sediment problems recognized in streams to specific hillslope sources or activities, if none can be identified otherwise;
 - b. Discriminate among the rates, effects, and hazards of various mass wasting and surface-erosion processes, in basins where both are significant sediment sources;
 - c. Document the relative contributions of chronic and intermittent processes (e.g., related to great storms); or
 - d. Calculate rates of erosion, sediment transport, and storage when those are required (for example, if stream enhancement is contemplated).

Level 2 specialists may modify decision criteria for hazard ratings as additional information is obtained. The report must document the results of the analysis, and provide sufficient information to support the decision criteria and potential-impact ratings.

Mass Wasting Assessment Report

All information generated by an assessment becomes part of the record; that produced in Level 1 will be available for the Level 2 analysis and/or any later assessments. The following mass wasting assessment products are forwarded for use in the routing, synthesis, and prescription modules:

- I. Title page** with name of watershed analysis, name of module, level of analysis, signature of qualified analyst(s), and date
- II. Table of contents**
- III. Maps**
 - Mass wasting landslide inventory (map A-1)
 - Mass wasting map units and hazard potential ratings (map A-2)
- IV. Summary Data**
 - Mass wasting inventory data (form A-1)
 - Mass wasting map unit description form (form A-2)
 - Mass wasting summary table (form A-3)
 - Summary of mass wasting and delivery potential (form A-4) -- **optional**
- V. Summary Text**
 - Summary geologic and physiographic setting pertinent to mass wasting interpretations
 - Study methods
 - Summaries of analysis and results
 - Descriptions of mass wasting map units
 - Description and explanation of mass wasting potential ratings
 - Statement on trigger mechanisms
 - Recommendations for Level 2 (at Level 1 only)
 - Statement of the author's confidence level in the analysis and results
 - Does module report address all critical questions?
- VI. Other Information (optional)**
 - Monitoring strategies and design and implementation suggestions
 - Learning resources (a.k.a., references, bibliography) section
 - Acknowledgments section

Confidence

Include in the report a consideration of the confidence in the assessment and work products.

Example of confidence statement

The Hemlock Creek watershed was very complex, containing broad alluvial valleys, deeply and freshly incised tributaries, and rolling upland plateaus. A mixture of volcanic bedrock and glacial deposits complicates the geologic story.

The road network was well established and passable in the northern half of the watershed (Fern, Gneiss, and Alabaster sub-basins), but road washouts and a sparse network in Lodgepole and Cobble Creeks precluded much field checking there. Watershed-wide, 53 percent of the landslides were observed in the field; however, only 15 percent were checked in the Lodgepole Creek and Cobble Creek sub-basins.

The aerial photo coverage went back to 1943 for the entire basin, although those photos had poor resolution. Starting in 1964, photos were available every five to seven years; however, the Cobble Creek sub-basin was not photographed consistently.

The owner provided excellent records regarding harvest history and fires; however, only anecdotal information was provided for road maintenance (i.e., washouts, erosion, landslide blockage).

Confidence in assessing natural potential for mass wasting under unmanaged conditions:

There were good opportunities for observing naturally occurring landslides. Both Lodgepole and Cobble Creek sub-basins had large areas of forest with no previous forest practices. These areas included all the mass wasting map units defined for this WAU except for MWMU 7. In addition, the 30-year period of aerial photo coverage included two large storm events (1973 and 1985, with photos available for 1975 and 1988), so the conditions under which landsliding is likely to occur were included in the historic record. Field verification of landslide sites identified on aerial photos indicated high accuracy in aerial photo interpretations.

Assessment of the natural mass wasting potential also relied on field interpretations: examples of all MWMUs were visited.

Confidence in assessing sensitivity to forest practices:

Opportunities for observing the effects of forest practices on mass wasting activity varied widely between MWMUs. Road building and clearcut harvesting have occurred extensively in low-gradient valley

bottom and upland areas (MWMUs 4 and 5); moderate activity occurred in the higher-elevation areas underlain by ultramafic bedrock (MWMU 3). Two large storms occurring over the course of the aerial photo record provided conditions conducive to landsliding; unfortunately, much of the valley-side harvesting was done after 1985, thus reducing the likelihood of observing any effects of forest-practice activities. Additionally, forest practice techniques have changed over the course of the aerial photo record, so some inferences of sensitivity to forest practices may be based on techniques no longer in use.

Confidence in mapping accuracy:

MWMU polygons were delineated on the map using characteristics discerned from 1:24,000-scale topographic maps, 1:100,000-scale geologic maps, 1:24,000-scale soil-type maps, and 1:12,000-scale aerial photos. Mapping accuracy was field-checked at only a limited number of sites (in Fern, Gneiss, and Alabaster sub-basins). Overall, a high level of confidence in mapping accuracy can be applied to Fern, Gneiss, and Alabaster sub-basins; a moderate degree of confidence in Lodgepole Creek, and a low level of confidence in Cobble Creek (because of both limited photographic coverage and restricted access to the basin for field checking).

Map resolution:

Map polygons are drawn in an effort to include all areas matching the particular MWMU description. At a 1:24,000 map scale, areas having linear extent less than about 250 feet may not be resolved. Forest canopy further increases the minimum size of landscape features that can be discerned. It is probable, therefore, that within any MWMU polygon there are small areas that belong to a different MWMU, e.g., there may be areas of low hazard contained within mapped high-hazard polygons, and vice-versa. In all cases, the ultimate determination as to which MWMU any particular site belongs must rely on field conditions.

Skill of the analyst:

The mass-wasting module analyst, Ms. Crystal Peneplain, has performed three mass-wasting modules, one in eastern Washington and two in western Washington. She has been working on forest geomorphological problems since 1984.

Acknowledgments

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References

- Benda, L., and T. W. Cundy.** 1990. Predicting deposition of debris flows in mountain channels. *Canadian Geotechnical Journal*. v. 27, pp. 409-417.
- Chatwin, S. C., D. E. Howes, J. W. Schwab, and D. N. Swanson,** 1991, A guide for management of landslide-prone terrain in the Pacific Northwest. British Columbia Ministry of Forests, Land Management Handbook 18, 212 p.
- Coho, C., and S. J. Burges,** 1994, Dam-Break Floods in Low Order Mountain Channels of the Pacific Northwest, Water Resources Series Technical Report No. 138, Dept. of Civil Engineering, Univ. of Washington, Seattle, TFW-SH9-91-001, 23 p.
- Costa, J. E., and R. L. Schuster,** 1988, The formation and failure of natural dams. *Geol. Society of America Bulletin*, v. 100.7, pp. 1054-68.
- Dietrich, W. E. and Dunne, T.,** 1978, Sediment budget for a small catchment in mountainous terrain: *Z. Geomorphology Supplement* 29, pp. 191-206.
- Eisbacher, G. H., and J. J. Clague.** 1984. Destructive mass movements in high mountains: hazards and management. *Geologic Survey of Canada*, pp. 8-16, 230 p.
- Fiksdal, A. J., and M. J. Brunengo,** 1981, Forest slope stability project, phase II. Wash. Dept. of Ecology, Technical Report 81-14, 62 p.
- Howes, D. E.,** 1987, A terrain evaluation method for predicting terrain susceptible to post-logging landslide activity - a case study from the Coast Mountains of British Columbia. British Columbia Ministry of Environment and Parks (MOEP), Technical Report 28, 38 p.
- Howes, D.E., and E. Kenk,** 1988, Terrain classification system for British Columbia (rev'd ed). British Columbia Ministry of Environment (MOE), Manual 10, 90 p.
- Ice, G. G.,** 1985, Catalog of landslide inventories for the Northwest. National Council of the Paper Industry for Air and Stream Improvement (NCASI), Technical Bulletin 456, 78 p plus appendices.
- Johnson, A. C.,** 1990, The effects of landslide dam-break floods on the morphology of channels. [Unpubl master's thesis], College of Forest Resources, Univ. of Washington; TFW-SH17-91-001, 90 p.

Kennard, P., 1994 Road Assessment Procedure (RAP), consultant report to the Weyerhaeuser Company, Tacoma, WA.

Manson, C. J., 1984, Index to geologic and geophysical mapping of Washington, 1899-1983. Wash. Division of Geology & Earth Resources (WDGER), Information Circular 77, 56 p.

Manson, C. J., 1994, Preliminary bibliography and index of the geology and mineral resources of Washington, 1993. WDGER, Open File Report 94-15, 102 p.

Manson, C. J., 1995, Geologic and geophysical mapping of Washington, 1984-1994; and Theses on the geology of Washington 1986-1994; WDGER, Open File Report 95-2, 41 p.

Montgomery, D. R., and W. E. Dietrich, 1994, A physically-based model for the topographic control on shallow landsliding: Water Resources Research, v. 30.4, pp. 1153-1171.

Pentec Environmental, Inc., 1991, Methods for testing effectiveness of Washington forest practices rules and regulations with regard to sediment production and transport to streams: report submitted to Wash. Dept. of Natural Resources, TFW-WQ8-91-008, 100 p.

Pierson, T. C., and J. E. **Costa**, 1987, A rheologic classification of subaerial sediment-water flows: in Costa, J. E., Wieczorek, G. F., eds., Debris flows/avalanches - process, recognition, and mitigation: Geol. Society of America, Reviews in Engineering Geology, v.7, pp. 1-12.

Rib, H. T., and **Ta Liang**, 1978, Chapter 3, Recognition and identification; in R. L. Schuster and R. J. Krizek, editors, Landslides: analysis and control. National Academy of Sciences, Transportation Research Board Special Report 176, pp. 34-80.

Shaw, S. C., and D. **Johnson**, 1995, Slope morphology model derived from digital elevation (DEM) data: Wash. Dept. of Natural Resources - Forest Practices Division OFR 94-1.

Sidle, R. C., A. J. **Pearce**, and C. L. **O'Loughlin**, 1985, Hillslope stability and land use. American Geophysical Union, Water Resources Monograph 11, 140 p.

Swanson, F.J., and R. J. **Janda**, T. Dunne, D. N. Swanston, 1982, Sediment budgets and routing in forested drainage basins: USDA Forest Service General Technical Report PNW-141, 165 p.

U. S. Geological Survey, 1992, Washington Index to topographic and other map coverage [catalogue]. U.S.G.S. National Mapping Program, 48 p.

Varnes, D. J., 1984, Landslide hazard zonation: a review of principles and practice. UNESCO Natural Hazards series n. 3, 63 p.

Wieczorek, G. F., 1984, Preparing a detailed landslide-inventory map for hazard evaluation and reduction. Assoc. of Engineering Geologists Bulletin, V. XXI.3., pp. 337-342.

Wu, T. H., C. J. **Merry**, M. Abdel-Latif, C. P. Benasly, 1993, Landslide hazard mapping - 1. Estimating piezometric levels: report submitted to Wash. Dept. of Natural Resources, TFW-SH15-93-001, 100 p.

Suggested Reading

Benda, L., G. W. Thorsen and S. Bernath, Report of the I.D. team investigation of the Hazel landslide of the North Fork of the Stillaguamish River: Wash. Dept. of Natural Resources.

Benda, L., and W. Hang, 1990. Accounting for the stochastic occurrence of landslides when predicting sediment yields: In: International Symposium on Tropical Erosion, Suva, Fiji: IAHS Publication 192.

Eide, J., 1990, a 48-year sediment budget (1942-1989) for Deer Creek basin, Washington [Unpubl. master's thesis]: Bellingham, Western Washington University, 122 p.

Hammond, C., S. M. Miller and R. W. Prellwitz, 1988, Estimating the probability of landslide failure using Monte Carlo simulations: In: Proceedings of the 24th Engineering Geologists and Soils Symposium, Moscow, Idaho: University of Idaho. pp. 319-331.

Hammond, C., and D. Hall, S. Miller, P. Swetik, 1992, Level I Stability Analysis (LISA), documentation for Version 2.0: Intermountain Research Station USDA Forest Service, Moscow, Idaho, General Technical Report INT-285, 190 p.

Kelsey, H. M., 1980, A sediment budget and an analysis of geomorphic process in the Van Huzen River basin, north coastal California, 1941-1975: Geological Society of America Bulletin, Part II, v. 91, pp. 1119-1216.

Pacific Watershed Institute, 1991, Prototype watershed analysis: report submitted to Wash. Dept. of Natural Resources, TFW-CEI-92-001, 113 p. plus appendices.

Reid, L., and T. Dunne, 1992 [draft], Rapid evaluation of sediment budgets: Pacific Southwest Research Station, USDA Forest Service, Albany, Calif., draft technical report.

Form A-1 Mass Wasting Inventory Data

[illegible]

Form A-2 Mass Wasting Map Unit Description**MWMU Number:****Description:****Materials:****Landform:****Slope:****Elevation:****Total Area:****MW Processes:****Non-road-related Landslide Density: (optional)****Forest Practice Sensitivity:****MW Potential:****Delivery Potential:****Delivery Criteria Used:****Hazard Potential Rating:****Trigger Mechanism(s):****Confidence:****Comments:**

Form A-3 Mass Wasting Summary Table

ACTIVITY	MASS WASTING FEATURE				Totals
	Shallow Rapid LS	Large Persistent Deep-Seated Failures	Small Sporadic Deep-Seated Failures	Debris Torrent	
Clear Cut 0-20 years					
Clear Cut 20-50 years					
Partial Cut					
Road					
Stream Crossing					
Landing					
Other Forest Practices					
Wildfire					
Mature Forest					
Non-Forest Land Use					
Totals					

Form A-4: Summary of Mass Wasting and Delivery Potential

MWMU	Mass Wasting Potential	Delivery Potential	Potential Hazard Rating